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The Impact of Feedback on Disk Galaxy Scaling Relations

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Abstract. We use a disk formation model to study the effects of galactic outflows (a.k.a. feedback) on the rotation velocity - stellar mass - disk size, gas fraction - stellar mass, and gas phase metallicity - stellar mass scaling relations of disk galaxies. We show that models without outflows are unable to explain these scaling relations, having both the wrong slopes and normalization. The problem can be traced to the model galaxies having too many baryons. Models with outflows can solve this “over-cooling” problem by removing gas before it has time to turn into stars. Models with both momentum and energy driven winds can reproduce the observed scaling relations. However, these models predict different slopes which, with better observations, may be used to discriminate between these models.

1. Introduction

Galactic outflows are widely observed in galaxies that are undergoing, or have recently undergone, intense star formation: e.g. Nearby starburst and IR bright galaxies (Martin 2005); Post starburst galaxies at redshift $z \simeq 0.6$ (Tremonti et al. 2007); Normal Star forming galaxies at redshift $z = 1.4$ (Weiner et al. 2009) and Lyman Break Galaxies at redshifts $z \simeq 3$ (Shapley et al. 2003). However, whether or not galactic outflows play an important role in determining the properties of galaxies has yet to be determined.

A clue that outflows might play an important role in galaxy formation comes from fact that galaxy formation is inefficient. The galaxy formation efficiency, ϵ_{GF}, defined as the ratio between the galaxy mass (in stars and cold gas) to the total available baryons available to that galaxy (the cosmic baryon fraction times total virial mass of the halo) peaks at $\simeq 33\%$. This has been determined by galaxy-galaxy weak lensing studies (Hoekstra et al. 2005; Mandelbaum et al. 2006), which are independent of ΛCDM, and galaxy-halo number abundance matching (e.g. Conroy & Wechsler 2009), which assumes the ΛCDM halo mass function as a prior.

A low peak galaxy formation is a problem because cooling is expected to be efficient in typical galaxy mass haloes (with virial velocities ranging from $V_{\rm vir} \simeq 60$ to $\simeq 150\,\mathrm{km/s}$). At low masses (below $V_{\rm vir} \simeq 30\,\mathrm{km/s}$) cooling is suppressed by UV photo heating, while at high masses (and high virial temperatures) cooling is inefficient due to the physics of radiative cooling. Thus another mechanism is needed to suppress galaxy formation, in the halo mass regime one would expect

it to be highly efficient. Galactic outflows driven by supernova (SN) or young massive stars are the prime candidate, having been successfully invoked in semi-analytic galaxy formation models to explain the shallow faint end of the galaxy luminosity function (e.g. Benson et al. 2003).

1.1. Simple feedback models

The simplest, physically motivated, feedback models can be described by 2 parameters: the mass loading factor, η, defined as the ratio between the mass outflow rate, and the star formation rate; and the wind velocity, $V_{\rm wind}$. These two parameters are related by the mechanism that drives the wind, and the relation between the wind velocity and the escape velocity, $V_{\rm esc}$. Feedback models can be divided into 3 broad categories:

- **Constant Velocity Wind**: Assumes $V_{\rm wind} = const.$, which implies $\eta = const.$ A popular example is that implemented by Springel & Hernquist (2003), which assumes $V_{\rm wind} = 484$km/s and $\eta = 2$. This corresponds to 25% of the SN energy being transferred to the wind (i.e. $\epsilon_{\rm FB} = 0.25$).
- **Momentum Driven Wind**: Assumes $V_{\rm wind} = 3\sigma \simeq V_{\rm esc}$, where σ is the velocity dispersion of the galaxy. Momentum conservation implies $\eta = (300/V_{\rm wind})$ (this assumes 100% momentum conservation) (Murray Quataert & Thompson 2005).
- **Energy Driven Wind**: Assumes $V_{\rm wind} = V_{\rm esc}$, energy conservation implies $\eta = \epsilon_{\rm FB}\, 10(300/V_{\rm wind})^2$, where $\epsilon_{\rm FB}$ is the fraction of SN energy that ends up in the outflow (e.g. van den Bosch 2001)

Finlator & Davé (2008) showed that models with the momentum driven wind provide a better match to the stellar mass - gas phase metallicity relation at $z \simeq 2$ than models with a constant velocity energy driven wind, or models without galaxy winds. However, it is not clear that this is a convincing argument against energy driven winds because Finlator & Davé (2008) did not consider an energy driven wind with the same assumption that they made for the momentum driven wind i.e. $V_{\rm wind} \simeq V_{\rm esc}$.

Here we use a semi-analytic disk galaxy formation model to discuss the observational signatures of different feedback models on the scaling relations of disk galaxies. We address the following questions: 1) Can models without outflows explain these relations? 2) Can models with outflow explain these relations? and 3) Can the scaling relations be used to discriminate between different wind models?

2. The Disk Galaxy Formation Model

Here we give a brief overview of the disk galaxy evolution model used in this proceedings. This model is described in detail in Dutton & van den Bosch (2009). The key difference with almost all disk evolution models is that in this model the inflow (due to gas cooling), outflow (due to SN driven winds), star formation rates, and metallicity, are computed *as a function of galacto centric*

radius, rather than being treated as global parameters. The main assumptions that characterize the framework of these models are the following:

1. **Mass Accretion History**: Dark matter haloes around disk galaxies grow by the smooth accretion of mass which we model with the Wechsler et al. (2002) mass accretion history (MAH). The shape of this MAH is specified by the concentration of the halo at redshift zero;
2. **Halo Structure**: The structure of the halo is given by the NFW profile (Navarro, Frenk, & White 1997), which is specified by two parameters: the mass and concentration. The evolution of the concentration parameter is given by the Bullock et al. (2001) model with parameters for a WMAP 5th year cosmology (Macciò et al. 2008);
3. **Angular Momentum**: Gas that enters the halo is shock heated to the virial temperature, and acquires the same distribution of specific angular momentum as the dark matter. We use the angular momentum distributions of the halo as parametrized by Sharma & Steinmetz (2005);
4. **Gas Cooling**: Gas cools radiatively, conserving its specific angular momentum, and forms a disk in centrifugal equilibrium;
5. **Star Formation**: Star formation occurs according to a Schmidt type law on the dense molecular gas, which is computed following Blitz & Rosolowsky (2006);
6. **Supernova Feedback**: Supernova feedback re-heats some of the cold gas, ejecting it from the disk and halo;
7. **Metal Enrichment**: Stars eject metals into the inter stellar medium, enriching the cold gas.
8. **Stellar Populations**: Bruzual & Charlot (2003) stellar population synthesis models are convolved with the star formation histories and metallicities to derive luminosities and surface brightness profiles.

3. Results

3.1. Impact of Feedback on Velocity, Stellar Mass and Disk Size

Fig. 1 shows the impact of feedback on the rotation velocity, stellar mass, and disk size of a galaxy that forms in a halo with virial mass $M_{\rm vir} = 6.3 \times 10^{11} h^{-1} M_{\odot}$, and which has the median halo concentration and angular momentum parameters for haloes of this mass. The green lines show the observed scaling relations from (Dutton et al. 2007 and Shen et al. 2003). The circles show models with feedback efficiency varying from $\epsilon_{\rm FB} = 0$ to 1. The model without feedback results in a galaxy that is too small and which rotates too fast. The upper right panel shows the galaxy mass fraction $m_{\rm gal} = M_{\rm gal}/M_{\rm vir}$, and galaxy spin parameter $\lambda_{\rm gal} = (j_{\rm gal}/m_{\rm gal})\lambda$, where λ is the spin parameter of the halo and $j_{\rm gal} = J_{\rm gal}/J_{\rm vir}$ is the angular momentum fraction of the galaxy,

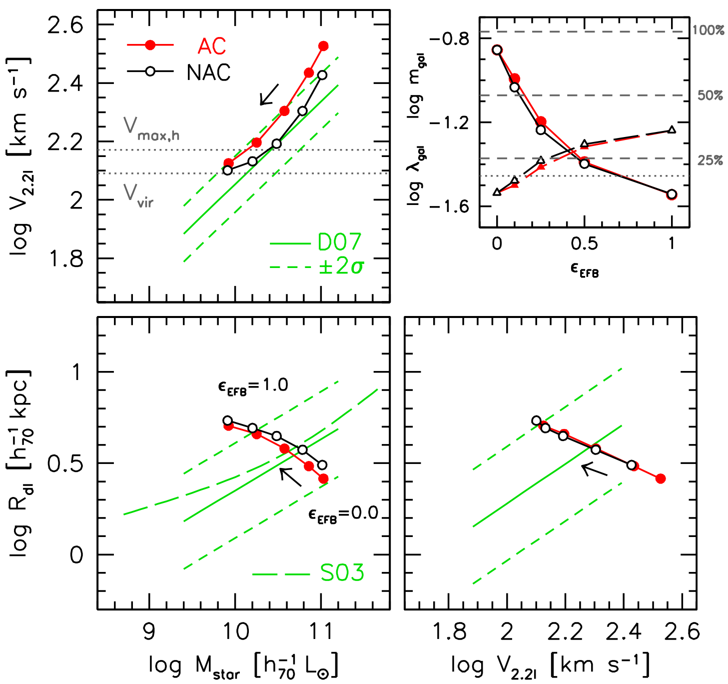

Figure 1. **Dependence of Velocity, Stellar Mass and Disk Size on Feedback:** Effect of feedback efficiency, $\epsilon_{\rm FB}$, for the energy driven wind, on the position of a galaxy with $M_{\rm vir} = 6.3 \times 10^{11} h^{-1} M_\odot$ in the VMR planes. The arrows indicate the direction of increasing $\epsilon_{\rm FB}$. Models with adiabatic contraction are shown with solid red symbols, models without adiabatic contraction are shown as black open symbols. The solid and dashed green lines in show the mean and 2σ scatter of the observed relations from Dutton et al. (2007, D07), assuming a Chabrier IMF. The long dashed green line shows the observed half-light radius stellar mass relation from Shen et al. (2003, S03). The panel in the top right shows the effect of feedback on the galaxy mass fraction, $m_{\rm gal}$ (circles), and galaxy spin parameter, $\lambda_{\rm gal}$ (triangles). The dashed horizontal lines show galaxy formation efficiencies of 100, 50, and 25 percent, the dotted horizontal line shows the spin parameter of the halo. As the feedback efficiency is increased the galaxy mass fraction ($m_{\rm gal}$) decreases, the galaxy spin parameter ($\lambda_{\rm gal}$) increases. This results in the rotation velocity decreasing, the stellar mass decreasing, and the size of the stellar disk increasing.

versus the feedback efficiency. This shows that the model galaxy without feedback has acquired 85% of the available baryons and 80% of the available angular momentum. The mass and angular momentum fractions are less than unity because cooling is not 100% efficient. The angular momentum fraction is less than the galaxy mass fraction because cooling occurs from the inside-out.

As the feedback efficiency is increased the galaxy stellar mass decreases, disk size increases and the rotation velocity decreases. These changes are primarily driven by the decrease in the galaxy mass fraction, $m_{\rm gal}$, and secondarily by the increase in the galaxy spin parameter, $\lambda_{\rm gal}$ (upper right panel). The increase in

galaxy spin parameter is the result of preferential loss of low angular momentum material, which helps to explain the origin of exponential galaxy disks, which are otherwise not naturally produced in a CDM cosmologies (Dutton 2009).

The upper left panel shows that models with adiabatic contraction (Blumenthal et al. 1986) (red points and lines) rotate too fast for all feedback efficiencies. For a model without adiabatic contraction (open circles and black lines) the zero point of the VM relation is reproduced for feedback efficiencies of $\epsilon_{\rm FB} \simeq 0.1 - 0.5$. In order for our models to produce realistic rotation velocities, in the models that follow we will assume the halo does not contract in response to galaxy formation.

3.2. Impact of feedback on disk sizes, gas fractions and metallicity

Here we discuss the impact of feedback on the scaling relations between disk size, gas fractions and gas phase metallicity with stellar mass. We discuss three feedback models: 1) no feedback; 2) momentum driven feedback; 3) energy driven feedback with $\epsilon_{\rm FB} = 0.25$. For each model we generate a Monte Carlo sample of galaxies, with halo masses logarithmically sampled from $M_{\rm vir} = 10^{10} - 10^{13}\, h^{-1} M_{\odot}$, log-normal scatter in halo spin parameter λ, halo concentration, c, and angular momentum distribution shape, α.

Disk Sizes: The upper panels of Fig. 2 show the disk size- stellar mass relation for our three models. As expected from Fig. 1, the model without feedback produces a size-mass relation with the wrong zero point, but also with the wrong slope. Models with feedback reproduce the zero point of the size-mass relation, but they predict different slopes: 0.26 for the momentum driven wind and 0.14 for the energy driven wind. The energy driven wind predicts a shallower slope because it is more efficient at removing gas from lower mass haloes, which (see Fig. 1) moves galaxies to lower masses and larger sizes. Observationally the correct slope is not clear, with values of 0.24 (Pizagno et al. 2005) and 0.28 (Dutton et al. 2007) and 0.14 (at low masses) to 0.39 (at high masses) from Shen et al. (2003) being reported. Thus a more accurate observational determination of the size-stellar mass relation would provide useful constraints to these models.

Gas Fractions: It has emerged in the last few years (Springel & Hernquist 2005; Hopkins et al. 2009) that the gas fraction of galaxies plays an important role in determining the morphology of galaxies after mergers. In particular galaxies with high gas fractions can re-form their disks after major and intermediate mass mergers. This removes a potential problem for the formation of bulgeless and low bulge fraction galaxies in ΛCDM, where intermediate and major mergers occur in the lifetime of essentially all dark matter haloes.

The middle panels of Fig. 2 show the gas fraction vs. stellar mass relation. The green points show observations from Garnett (2002), with a fit to the mean and scatter of this data shown by the solid and dashed lines. The model without feedback (left) produces galaxies that are too gas poor, especially for lower mass galaxies. This problem is the result of the disks being too small, and hence too high surface density, which results in more efficient star formation. The models with feedback both reproduce the observed relation, with the energy driven wind predicting a higher zero point.

Mass Metallicity: Finlator & Davé (2008) used the mass metallicity relation at redshift $z \simeq 2$ to argue in favor of momentum driven winds over energy

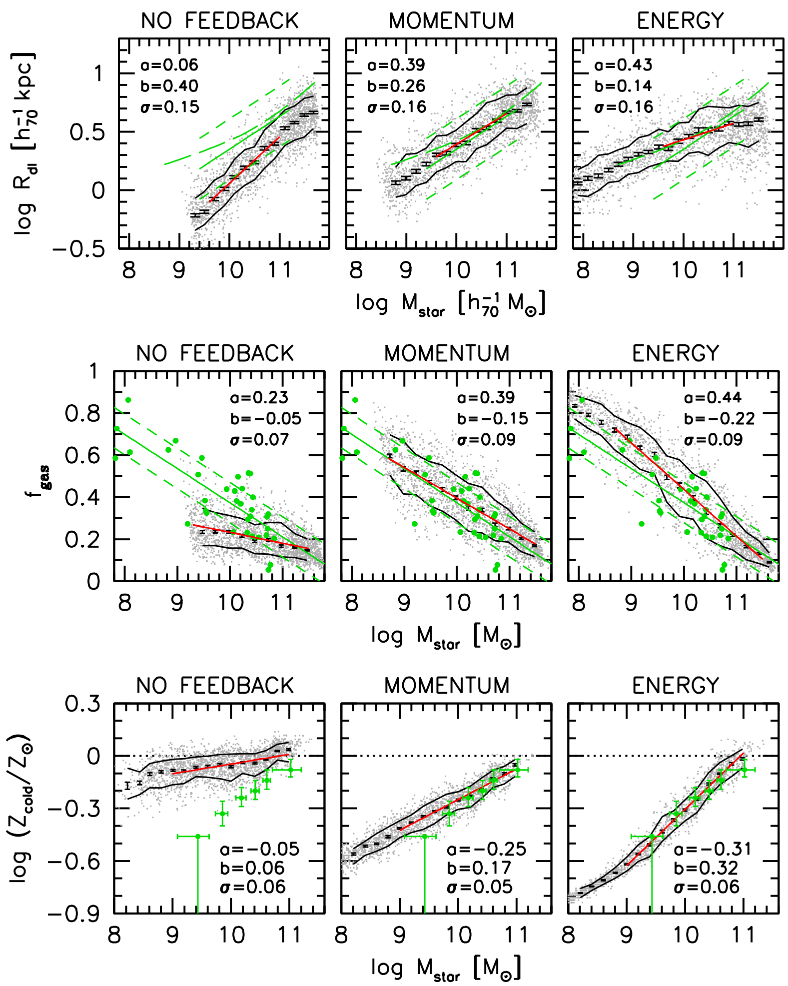

Figure 2. **Dependence of disk size, gas fraction and gas metallicity on feedback.** *Upper panels:* disk size - stellar mass; *Middle panels:* gas fraction - stellar mass, *Lower panels:* gas phase metallicity - stellar mass. The observed relations are given by green lines, points and symbols. The model galaxies are given by grey points, with the black lines showing the 14th and 86th percentiles in stellar mass bins. For the size-mass relation and gas fraction mass scaling relations the data (Dutton et al. 2007; Shen et al. 2003; Garnett 2002) and models are for redshift $z = 0$. For the metallicity-mass relation the data (Erb et al. 2006) and models are for redshift $z = 2.26$. The sizes, gas fractions and metallicities are coupled, and yield different slopes for different feedback models

driven winds (of constant velocity). The lower panels of Fig. 2 show the stellar mass - gas metallicity relation at $z = 2.26$. We confirm the result of Finlator & Davé (2008) that models without feedback do not reproduce the mass-metallicity relation, and that models with momentum driven winds provide a good match to the observations. However, we also show that models with energy driven winds provide a equally good match to the data. The energy and momentum driven winds do predict different slopes: 0.17 for momentum and 0.32 for energy, and

thus more accurate observations, and especially to lower stellar masses, may be able to distinguish between these two models.

4. Summary

We have used a semi-analytic disk galaxy formation model to investigate the effects of galaxy outflows on the scaling relations of disk galaxies. We find that

1) None of the scaling relations can be reproduced in models without outflows: model galaxies rotate too fast, are too small, are too gas poor and are too metal rich. These problems are driven by the high baryonic mass fractions of these galaxies.

2) Models with outflows can solve this problem by removing gas from galaxies before it has had time to turn into stars.

3) Models with momentum and energy driven winds provide acceptable fits to the observed disk size-stellar mass, gas fraction stellar mass, and gas metallicity - stellar mass relations. However, these models predict different slopes (due to the different scaling between mass loading factor and wind velocity). Thus more accurate observations will be able to discriminate between these models.

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